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SUPERCONDUCTIVITY FOR MIRROR FUSION

CARL D. HENNING

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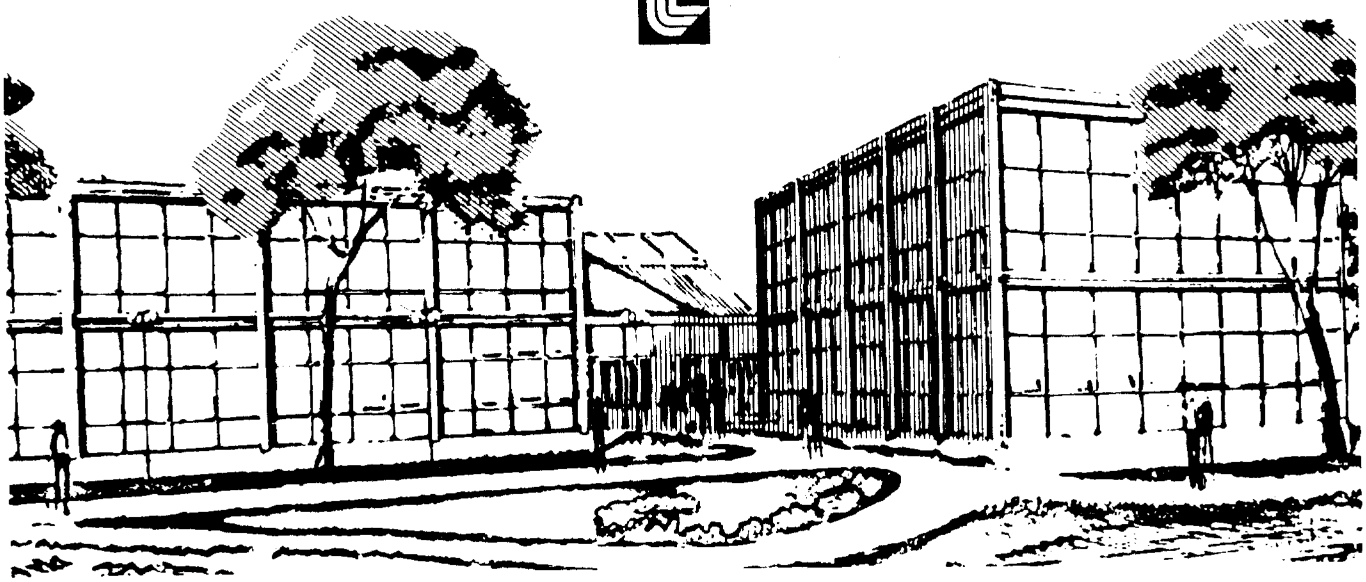

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ABSTRACT

Mirror experiments have led the way in applying superconductivity to fusion research because of unique requirements for high and steady magnetic fields. The first significant applications were Baseball II at LLL and IMP at ORNL, which used multifilamentary niobium-titanium and niobium-tin tape, respectively. Now the USSR at Kurchatov is building a smaller baseball coil with a 6.5 mm square multifilamentary niobium-titanium superconductor similar to the Baseball II conductor. However, the largest advance in fusion magnets will be used in the Mirror Fusion Test Facility (MFTF) now under construction at LLL. Improvements in the technology of the previous LLL experiment, Baseball II, have been made using new conductor joining techniques, a ventilated wrap-around copper stabilizer, and stronger structural welding methods. The MFTF coil winding is proceeding on a separate former to allow parallel construction of the main structure. Not only does this shorten the project schedule to equal that of other conventional constructions, but a second vacuum barrier is created between the magnet helium and the plasma environment for reliable operation. In the future, LLL envisions a superconducting version of the Tandem Mirror Experiment and a possible hybrid reactor leading to economical fusion power.

INTRODUCTION

The feasibility of Magnetic Fusion Energy is not expected to be demonstrated until the early 1980's. Yet, already efforts are being made to advance superconducting magnet technology to improve reactor power balances and construction economics. An example of this development and technology effort is the large coil program centered at ORNL[1]. This program, focused on Tokamak systems, is seeking to extend previous experience to include pulsed fields in large industrially fabricated magnets with simulated neutron and plasma environments. By comparison mirror fusion experiments have passed this stage of development because pulsed fields are not desired and because the early need for high, steady magnetic fields necessitated taking greater risks towards early development. As a result, except for the recent superconducting T-7 Tokamak[2] shown in figure 1, all of the previous large superconducting fusion magnets have been for mirror systems.

PAST AND PRESENT MIRROR MAGNETS

The earliest significant effort in superconducting mirror magnets was the Baseball II, constructed at LLL in 1970 and retired in 1977, shown in Figure 2. This magnet had an average spherical diameter of 1.2 meters and routinely operated with a peak field at the conductor of 6 tesla[3]. Other design characteristics of the magnet are shown in Table I. A 6.5 mm square niobium-titanium in copper composite superconductor was used. While the 0.6 mm filament diameter was found to be intrinsically stable, the filaments were not twisted to eliminate flux jumps. Also, conductor motion effects were observed such that the magnet was never charged to the design limit of 7.5 tesla. As in many magnets of unusual shape, the structural material was a major consideration. A nitrogen strengthened, manganese alloyed stainless steel (Nitronic

40) was used because of its high yield strength, 196 ksi. Toughness was measured to be adequate with a K_{1c} of 100 ksi-in$^{1/2}$ and weldability good with Inconel 182. No unusual problems were encountered during structure fabrication and usage except for the rapid work hardening, which made machining and forming more difficult.

Another early mirror magnet was the IMP constructed at ORNL in 1971, shown in Figure 3. Relatively late in the design stage, a change in conductor was made from niobium-titanium to niobium-tin tape[4]. This material, 1/2 inch wide and about .008 inches thick, was stabilized with .006 inches of high purity aluminum inter-leaving and insulated with a thin coating of graphite and aluminum oxide applied in an alcohol solution. The magnet performed well as a fusion experiment, and was later charged to the full design value of 9.3 tesla in 1978. Other characteristics of this early niobium-tin magnet are given in Table II. The performance was remarkable considering the very high perpendicular field component and the primitive understanding of dynamic stabilization at the time. However, extensive tests with cusped test coils in a large background field were able to produce enough experimental data to guide the design. Nitronic 40 was again used for the coil structure but no welds were attempted, the structure being machined from a solid billet.

Also in 1971, the NASA Bumpy Torus Experiment went into operation[5]. This 12 coil toroidal mirror (shown in Figure 4) produced axial toroidal fields of 3.3 tesla. Each magnet had a 19 cm bore and was arranged into a 1.52 m major diameter torus. Two different conductors were used; one was a 2.03 mm square composite with 14 niobium-titanium filaments in copper, while the other was a 2.16 mm round composite with 133 niobium titanium filaments.

Recently, the Ogra IIIB magnet was constructed at the Kurchatov Institute in the USSR for use in mirror research. Exact dimensions of the magnet are unavailable, but it is known to be about a quarter the size of Baseball II. It uses a 6.5 mm square niobium-titanium in copper composite conductor. Design fields are reported to be 3.7 tesla peak with a mirror ratio of 2:1.

The newest of the lineage of mirror magnets is for the Mirror Fusion Test Facility (MFTF) shown in Figure 5. This magnet is a Yin-Yang pair of 0.75 meter average minor radius and 2.5 meter average major radius. When the centers are overlapped by 0.7, meters the length between plasma mirrors becomes 3.6 meters. The central field is 2 tesla and the peak field which occurs in the minor radius is 7.68 tesla. Principal parameters of the magnet are given in Table III and further details will be reported by D. Deis, et al[6].

The MFTF conductor is the result of a two year development effort (Ref. 7). It consists of a 6.5 mm square niobium-titanium in copper composite wrapped in an embossed and perforated copper sheath as in Figure 6. This outer sheath of high purity copper provides the current path and heat transfer for stabilization. Figure 7 depicts the magnet load line and stability limit, as extrapolated from test coil results to be reported by D. Cornish, et al, (Ref. 8). While the conductor does exhibit cold-end recovery, the stability limit appears to extrapolate in accordance with the copper magneto resistance and a constant surface heat flux of 0.19 w/cm^2. Joints are made by cold welding the central core and resoldering the copper sheath around it. Currently, alternate joining methods are being considered to further increase the joint strength and raise the stability to equal that of the unjoined conductor.

In order to shorten the magnet construction schedule to three and one half years, commensurate with conventional copper coil experiments, the coil winding form (shown in Figure 8) was made separate from the structure. A further advantage of this method is that the space between the coil form and structure can be differentially pumped to serve as a guard vacuum preventing helium contamination of the plasma. Initially, Nitronic 40 with Inconel 625 welding was planned for the coil structure. However, fracture toughness limited the design stress to 80 ksi, such that equal performance could be obtained with a cheaper material of higher toughness, 304 LN stainless steel with 316 L welds. Presently 750,000 pounds of the steel is being ordered and General Dynamics-Convair is completing the structural design.

FUTURE MIRROR MAGNETS

To understand the future of mirror magnets one must look at past trends. In Figure 9 the progression of magnet stored energy is plotted; obviously magnets are getting bigger, especially for pure fusion reactors[9]. The use of fusion-fission hybrid systems lowers the system size, whether it is to be an energy producer or just a fissile fuel breeder[10].

Not so apparent is the need for higher fields. Single cell mirrors like MFTF are projected to need fields above 17 tesla in order to produce even the most modest energy multiplication. Such high fields could prove to be a technological and economic disadvantage. As a result, the tandem mirror configuration shown in Figure 10 has evolved[11]. Even so, the peak field envisioned for a tandem mirror reactor shown in Figure 11 remains at 17 tesla, and only the possibility of a field-reversed reactor, or a fusion-fission hybrid shown in Figure 12 of either geometry could reduce field requirements to 8.5 tesla. However, even these applications would greatly benefit from higher fields leading to better plasma confinement. Accordingly, Mirror Fusion definitely needs the development of larger and higher field magnets with operating fields up to 17 tesla. Obvious superconducting material candidates are niobium-tin and niobium-germanium. However, the brittle nature of all such A15 compounds is a great disadvantage in the inherently loose windings of a baseball seam type magnet. Perhaps the cable-in-tube concept of MIT would permit bonding of the conductor to reduce the source of conductor strain.

Better still would be a new, high-field alloy with enhanced strain capability approaching that of ductile niobium-titanium.

TABLE I.
Baseball II Magnet Characteristics

Central field	20 kG
Max. field at conductor	75 kG
Conductor type	Nb-Ti composite
Stabilizing copper resistance at 75 kG, 4.2°K	4.3×10^{-8} ohm-cm
Conductor dimension	1/4-in. square
Conductor length	40,000 ft
Conductor weight	10,000 lb
Design current	2,400 A
Ampere-turns	4,800,000
Inductance	6 Henrys
Stored energy	17 Megajoules
Equivalent heat flux at conductor surface	0.6 W/cm^2
Tensile force in conductor	1×10^6 lb

TABLE II.
IMP Characteristics

Coil Type - Mirror Coils with Ioffe Bars

Mirror Coil Bore - 14.7 cm

Mirror Coil Peak Field - 5.9 tesla

Mirror Coil Conductor - Nb-Ti in Cn

Mirror Coil Insulation - Spiraled Numex Paper

Ioffe Coil Design Field - 8.5 tesla

Current Density - 13,500 A/cm^2

Ioffe Coil Conductor - Nb_3Sn-Cn-S.S. Tape

Stabilizer - Aluminum Interleaving

Ioffe Insulation - Graphite - AL_2O_3

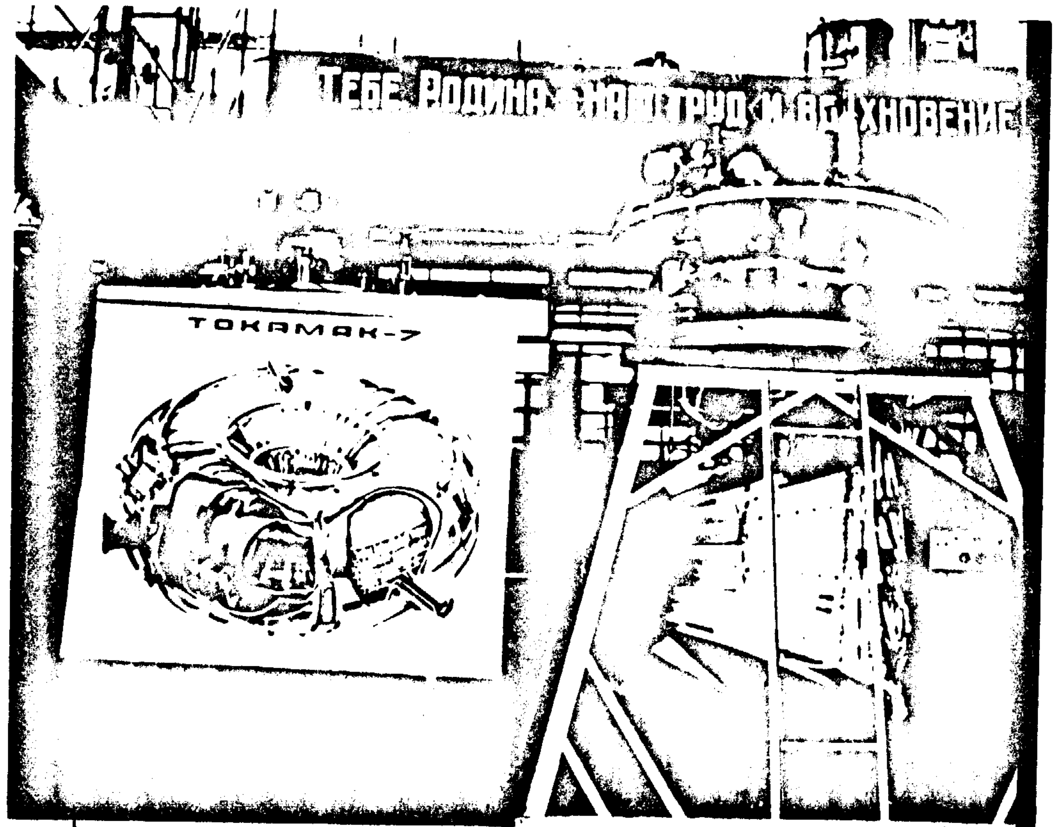
TABLE III.
Mirror Fusion Test Facility Parameters

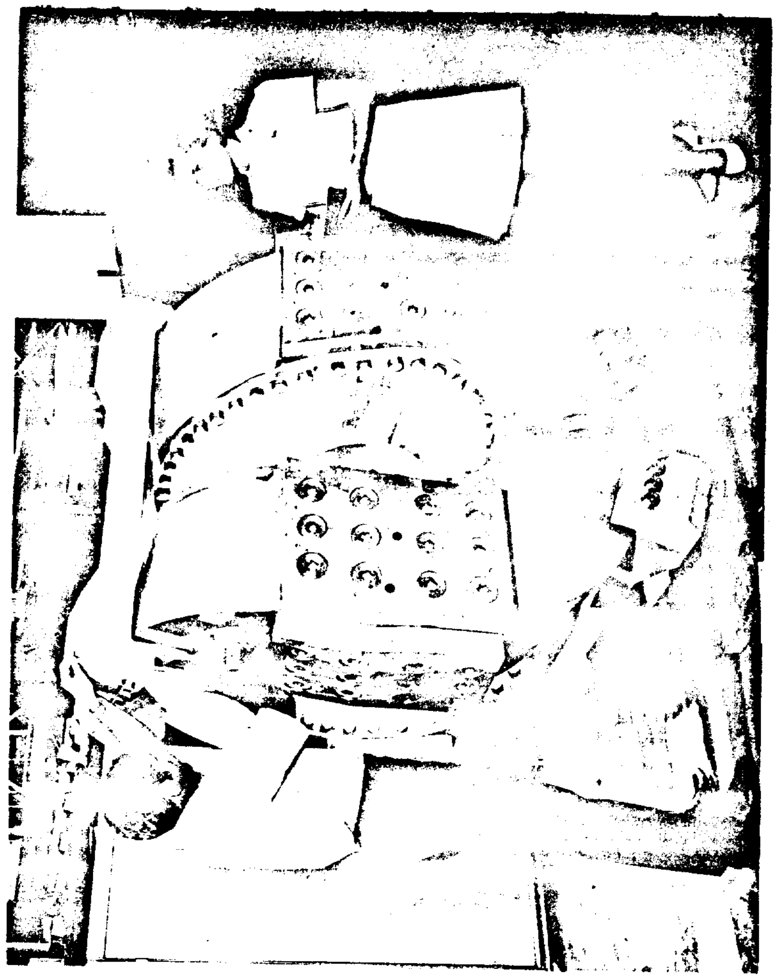
Type of Field	Minimum-B Mirror
Magnet Type	Displace Yin-Yang Pair
Major Radius (mean)	2.5 m
Minor Radius (mean)	0.75 m
Axial Half-Displacement	0.7 m
Coil Section	0.90 X 0.36 m
Mirror Length	3.6 m
Vacuum Center Field	2 T
Mirror Ratio	2.1/1
Coil Section Current Density	2525 A/cm^2
Conductor Current Density	3730 A/cm^2
Number of Turns (each coil)	1392
Ampere Turns (each coil)	8.04 MA
Stored Energy	409 MJ
Conductor Weight	54,430 kg
Total Weight	300,051 kg
Maximum Conductor Field	7.68 T
Conductor Current	5775 A
Critical Current	10 kA @ 7.5 T, 4.2 K
Conductor Operating Temperature	4.5 K

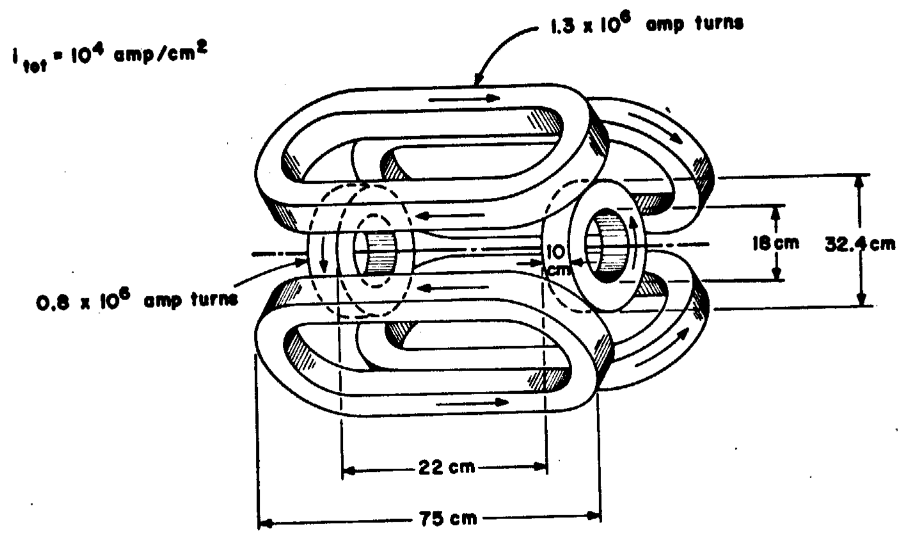
TABLE III. (contd)

Conductor Size	12.4 X 12.4 mm
Overall - Copper/ Superconductor	6.7/1
Stabilizer Copper Resistance Ratio	220/1
Copper Resistance at 4.5 K, 7.68 T	46 n /cm
Helium Cooled Surface Area	8.17 cm^2/cm
Required Heat Transfer Rate	.19 W/cm^2
Filament Number	480
Filament Diameter	0.20 mm
Twist Pitch	180 mm

1

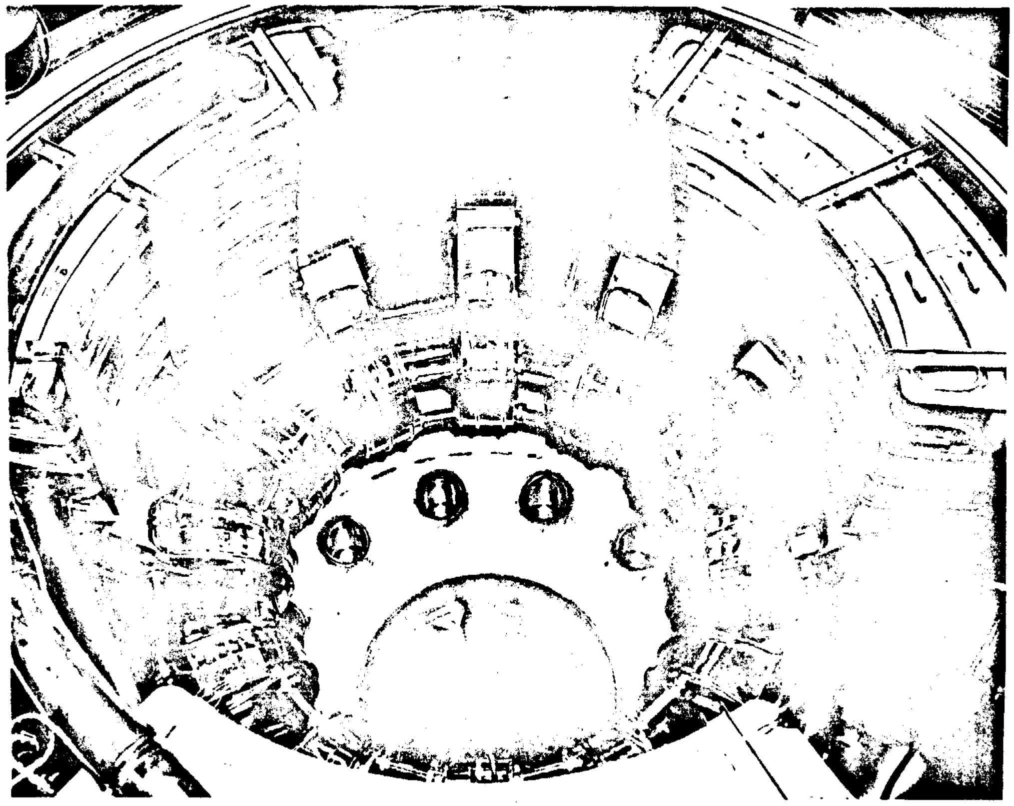




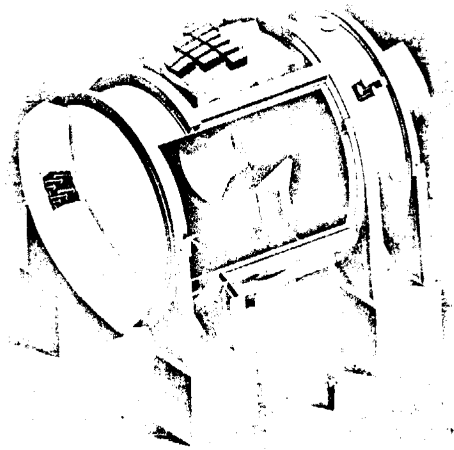


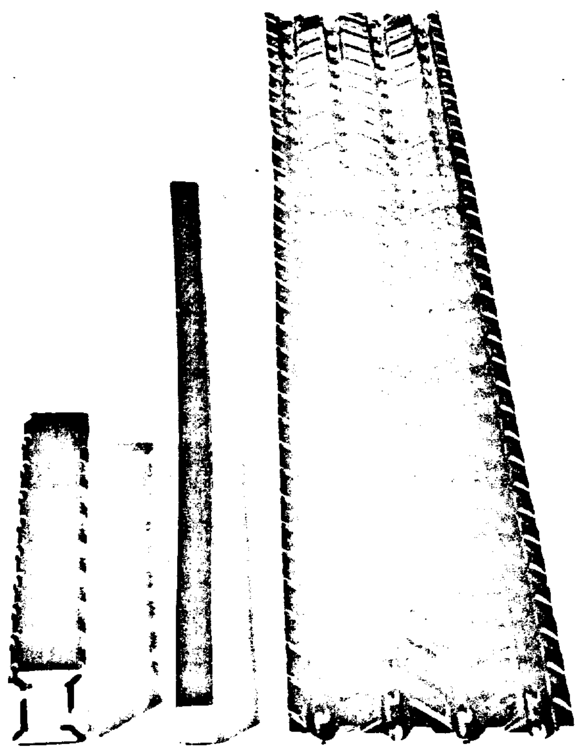
B_c = 20 kilogauss
B_m = 40 kilogauss
B_{mM} = 68 kilogauss
B_{IM} = 75 kilogauss

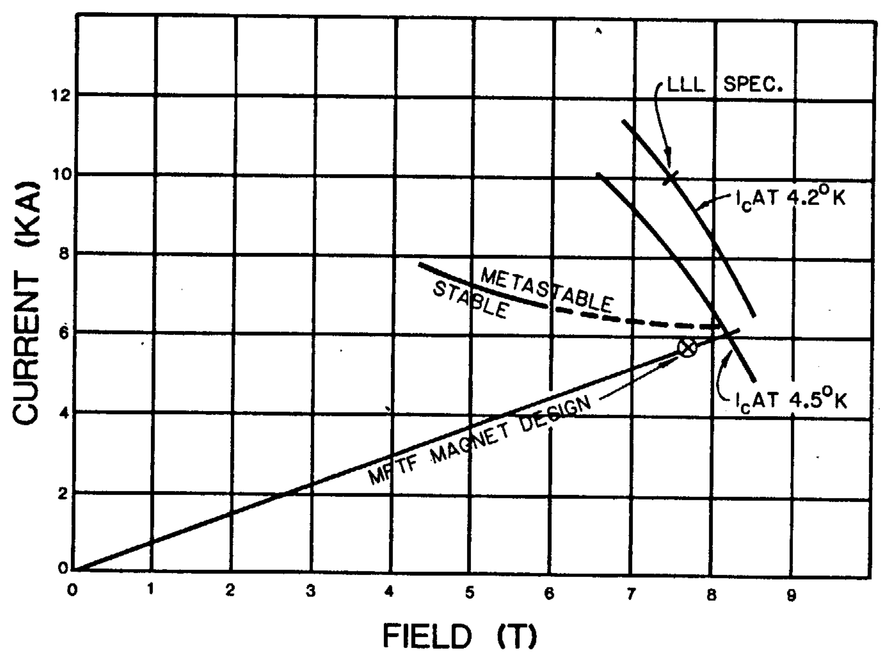
do not include these numbers

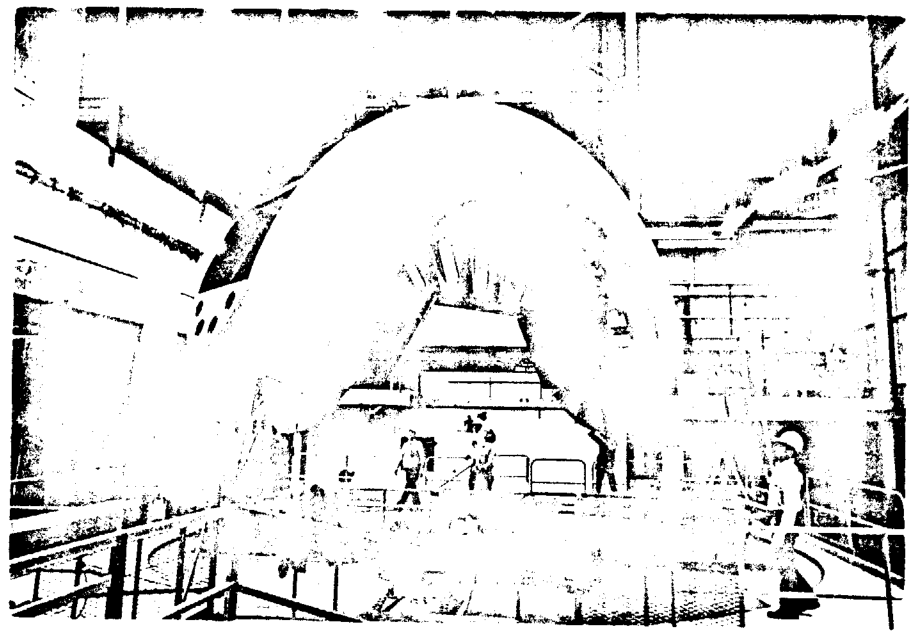


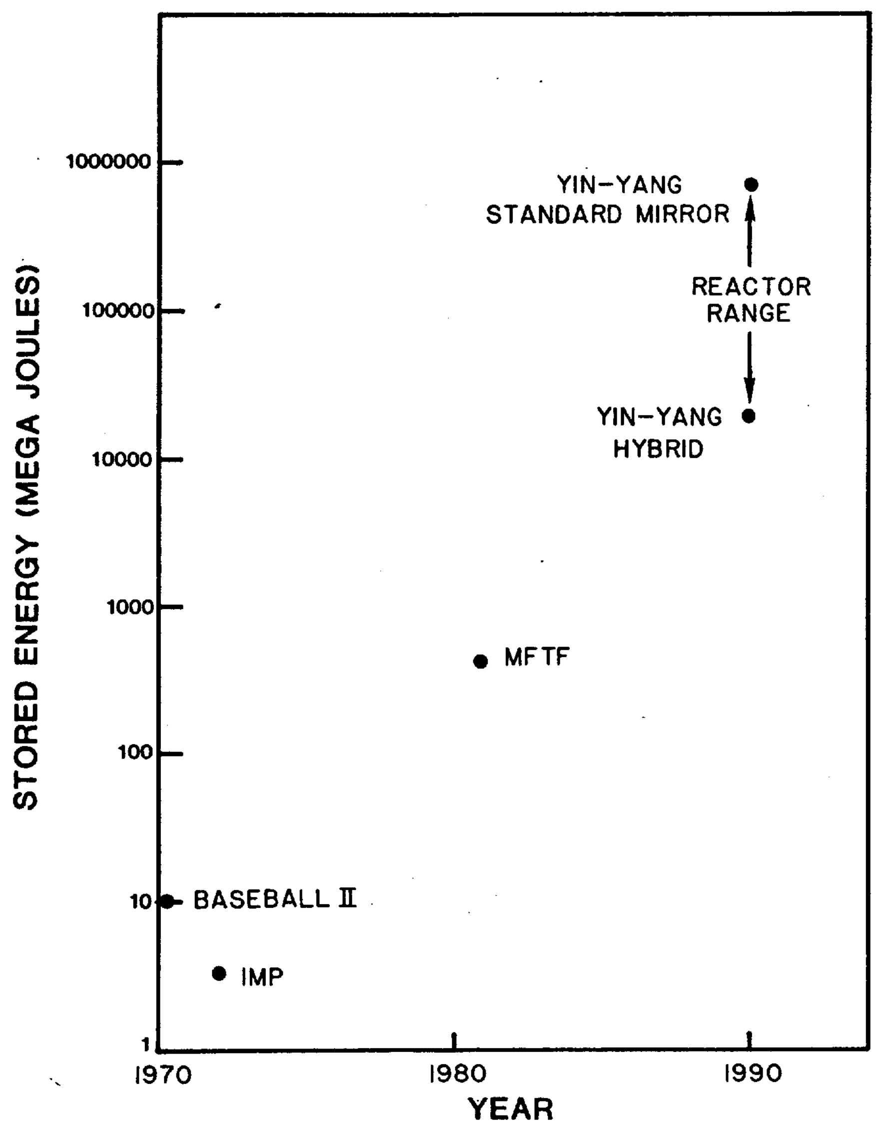
MIRROR FUSION TEST FACILITY VACUUM VESSEL



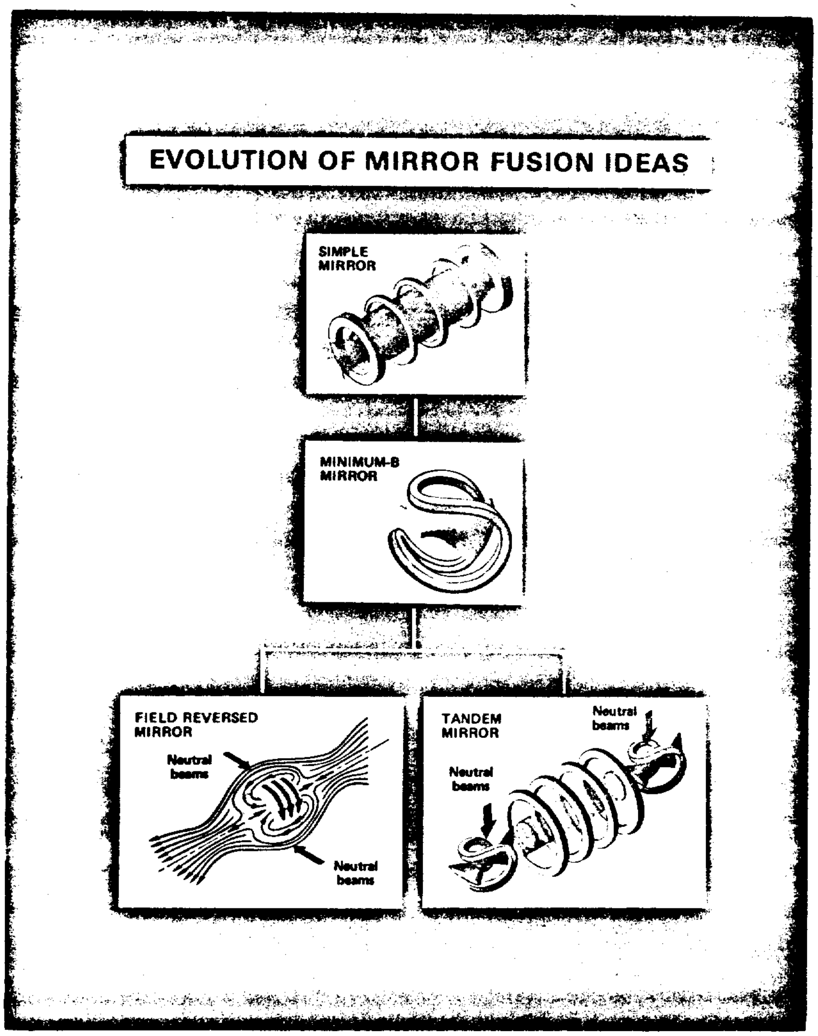



LLL SPEC.
I_c AT 4.2°K
METASTABLE
STABLE
I_c AT 4.5°K
MFTF MAGNET DESIGN
CURRENT (KA)
FIELD (T)
0
2
4
6
8
10
12
0
1
2
3
4
5
6
7
8
9

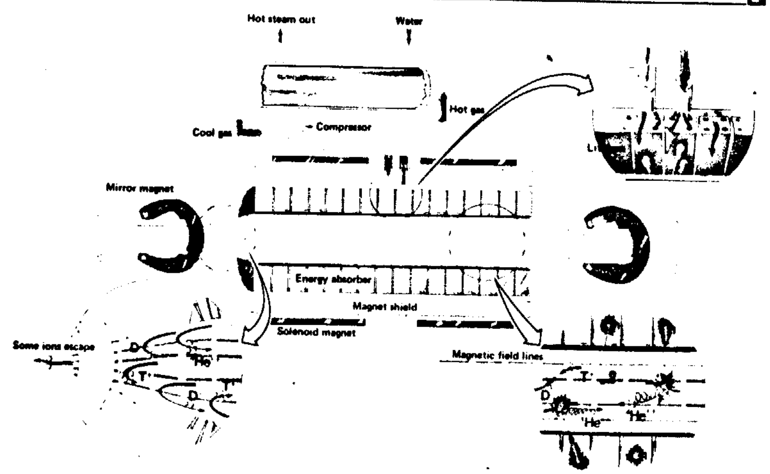




STORED ENERGY (MEGA JOULES)
1000000
100000
10000
1000
100
10
1
1970
1980
1990
YEAR
YIN-YANG
STANDARD MIRROR
REACTOR
RANGE
YIN-YANG
HYBRID
MFTF
BASEBALL II
IMP


EVOLUTION OF MIRROR FUSION IDEAS
SIMPLE MIRROR
MINIMUM-B MIRROR
FIELD REVERSED MIRROR
Neutral beams
Neutral beams
TANDEM MIRROR
Neutral beams
Neutral beams

PRINCIPLES OF A TANDEM MIRROR FUSION REACTOR



FUSION-FISSION MIRROR HYBRID REACTOR

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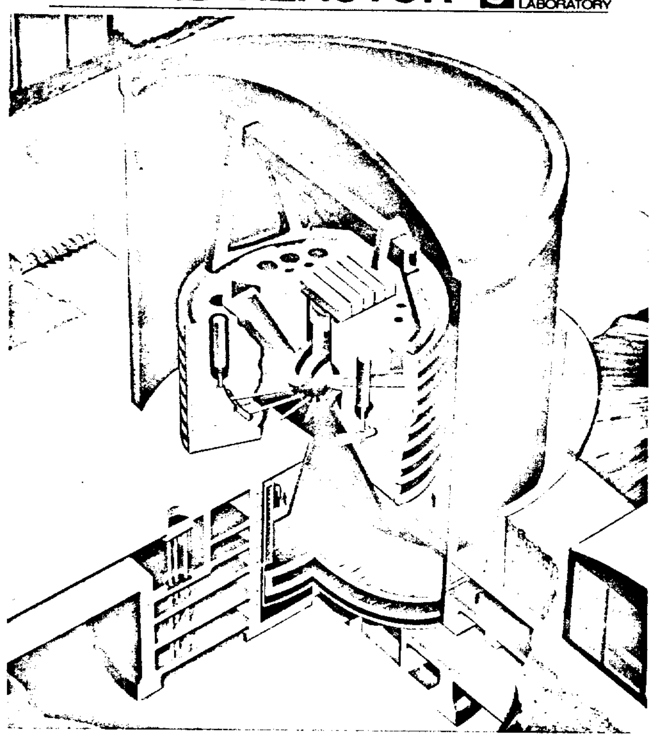

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